Economic and Engineering Constraints on the Restructuring of the Electric-Power Industry: A Consideration of Reactive-Power Ancillary Services

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1. Introduction

The proposed Comprehensive Electricity Competition Act exemplifies the movement to restructure the U.S. electric-power industry. This restructuring seeks to replace local regulated monopolies by introducing competition between generators of electric power. However, electric power cannot be stored, and laws of physics describe the constraints on how the U.S. electric-power transmission system can transport this commodity. Industry restructuring has demonstrated that competition can be introduced in the production of real power by generating units. But the possibility of gaming (the manipulation of the electric-power transmission system by generating units to place constraints on competitors through the rules governing the electric-power marketplace) exists, and one-of-a-kind resources (e.g., transmission lines) and localized phenomena (e.g., reactive compensation) may provide practical limits to competition.

Marketplace rules will determine how the restructured industry will perform. Presently, in California and in the east-central U.S., markets exist to promote competition in the generation of real power. However, these markets do not yet reward generating units for participation in security and reliability operations, such as the maintenance of nodal voltages. As such reliability operations impair the ability of the generating units to compete in the markets for the production of real power, business decisions sometimes require choosing between profit and infrastructure security. In these instances, the present marketplace rules may be considered to be detrimental to operating the infrastructure securely and reliably.

This paper explores economic and engineering constraints to competition in a restructured electric-power industry, with examples from reactive-power ancillary services.

2. Historical Example: Voltage-Control Issues in the Mid-Atlantic Area Council, July 1999

In 1999, the U.S. Department of Energy formed the Power Outage Study Team (POST) to study the power outages and other disturbances that occurred during the summer of 1999 and to recommend appropriate federal actions to avoid such disturbances in the future [1]. The motivations for this study team included the establishment of marketplaces within the electric-power infrastructure to permit the competitive sale and trade of power production.

The POST identified 38 characteristics of the restructured infrastructure that contributed to outages and disturbances in 1999. These findings were based on analyses of eight disturbances, ranging from outages from equipment failures to inadequate voltages caused by infrastructure operation.

The POST interim report identified that "there may not be adequate incentives for reactive power production." This finding was based on analyses of depressed voltages that occurred in the eastern interconnection, most notably in PJM, during high peak loads associated with two heat waves in the summer of 1999. PJM serves Pennsylvania, New Jersey, and Maryland, as well as certain other areas, and derives its acronym from this service area. On July 6th, a record peak load of 51.6 GW was recorded for the PJM system. During this peak, 500-kV transmission substations recorded voltages that were 94% of their nominal voltages. This low voltage was considered a serious problem, as the low voltage represents a reduced efficiency of power transmission and for the operation of equipment such as electric motors and power supplies. A nearly identical situation occurred on July 19th, also because of high peak loads during a heat wave.

A contributing factor identified in the POST report was that there was an economic disincentive for PJM's generating units to produce reactive power. Real power is when voltages and currents are in phase and are capable of accomplishing useful work. The peak load measured during the PJM disturbance was a measure of the real power demanded by customers. The component of the sinusoidal current that is $\pi/2$ radians out of phase from the voltage is called reactive power. Reactive power must be generated because of the inductive and capacitative attributes of electric-power transmission lines. However, the generation of reactive power requires a reduction in a generating unit's real-power generation capacity. At the time of the peak load during the disturbance, the market price for real power was over \$900 per megawatt-hour, whereas the price for reactive power was \$0 per megaVAR-hour. This price difference provided no incentive for the production of reactive power and directly contributed to the unacceptably low voltages during the system disturbance.

3. Reactive-Power Generation and Voltage Control

Figure 1 shows a schematic of a simple transmission system comprised of a generating unit, a transmission line, and a customer load. The customer demand is a constant 300-MW real-power load. In order to maintain the desired voltage at the generating unit, the generator must produce this real power, plus reactive power that is absorbed by the inductive and capacitative attributes of the transmission line, as well as some additional real power that is dissipated as losses in the transmission line. In this example, the generating unit must produce 304.18 MW of real power (98.6% transmission efficiency) and 18.53 MVAR of reactive power to maintain the desired voltage at the generation node. The voltage at the customer node is 98.4% of the nominal operating voltage, with this reduction in voltage caused by the current flow through the transmission line.

Figure 2 shows a second example, with the generation farther removed from the customer node. The current must flow through three identical transmission lines to reach the customer. In this example, the generating unit must produce 313.98 MW of real power (95.5% transmission efficiency) and 64.87 MVAR of reactive power. The voltage at the customer node in this case is 93.1% of the nominal operating voltage. The increase of transmission distance by a factor of 3 resulted in an increase in transmission losses by a factor of 3.21, and an increased voltage reduction at the customer node by a factor of 4.31. With the addition of 65 MVAR of reactive generation located at the customer node, the voltage measured at the customer node is restored to 98.4% of the nominal operating voltage. However, voltages at the intermediate transmission nodes between the generator and customer are lower than at either the generator or customer nodes.

These examples show the role of reactive-power production in controlling node voltages throughout an electric-power transmission system. As the distance between the generating unit and the customer increases, the reactive power required for voltage control increases. Although desired amounts of real power can be transmitted long distances, reactive generation must be distributed throughout the transmission system to provide sufficient voltage support. This requirement for distribution of reactive generation throughout a transmission system places a constraint on the establishment of a marketplace that would reward the generation of reactive power. The limited capability of the transmission system to transport reactive-power a significant distance without disrupting the node voltages near the source of reactive generation can limit competition by constraining the resources that can compete effectively for demand opportunities. In establishing a market, the process of deregulation must assure sufficient diversity of competitors of reactive generation exists to prevent local monopolies on the ancillary service of reactive-power generation, or by creating regional market rules that prevent such local monopolies from exerting their market power.

4. Hypothetical Example: Voltage-Control Issues for the San Diego Region of WSCC

The continental United States, Canada, and portions of Mexico are linked by a common electric-power transmission infrastructure. Within this infrastructure are AC interconnections; subsets of the grid that are connected by AC transmission lines and where all of the generating units operate at exactly the same frequency. Figure 3 shows these interconnections: the vast Eastern Interconnection, the Western Systems Coordinating Council (WSCC), Texas, and Quebec.

The WSCC interconnection contains the California Independent System Operator (Cal-ISO). The Cal-ISO was established by mandate of the California legislature to oversee the results of a competitive marketplace for real-power generation in California. Cal-ISO oversees the generation schedules produced by the marketplace, to relieve transmission congestion and assure adequate voltage control.

The transmission system formerly operated by San Diego Gas and Electric (SDG&E) is a portion of the Cal-ISO system and the WSCC. This transmission system is shown in some detail in Fig. 4. The SDG&E system contains 214 nodes including 27 generating units. Data from Cal-ISO show a forecast total SDG&E load at the time of the coincidental WSCC 1999 summer peak of 3424.6 MW, with 1932.8 MW of generation. Most of this generation comes from units at two generating stations, Encina and South Bay. These are both natural-gas-fueled generating stations. The remainder of the real-power demand is satisfied by power that is transmitted long distances to reach the SDG&E grid.

As an experiment, we wish to examine the SDG&E grid by hypothesizing the same type of conditions that occurred in PJM in July 1999. Specifically, consider the generation to be constrained by real-power production, as if all capacity were used to provide real power so that no reactive-power generation could occur. Allow normal reactive-power generation at the other units throughout WSCC, to determine if sufficient reactive power will be transmitted into the SDG&E grid while maintaining the desired voltages at the generating units elsewhere in WSCC. Results of this experiment were obtained by computer simulation of the WSCC power flow.

In the base case, there is considerable reactive-power production by the SDG&E units, particularly at Encina and South Bay. The reactive-power production at Encina is 114 MVAR, and at South Bay is 73 MVAR. Also, there is considerable reactive compensation by capacitors at substations, with over 500 MVAR of capacitors throughout the SDG&E grid. The largest capacitors are at the Main St., Miguel, and Penasquitos substations, at 100 MVAR each. For the base-case power flow in WSCC, the average substation node voltage in the SDG&E grid is 101.4% of the nominal operating voltage.

Next, we constrain the SDG&E generating units to produce no reactive power. For this case, the average SDG&E substation node voltage was 97.9% of the nominal operating voltage.

Finally, we constrain the SDG&E generating units to produce no reactive power, and also remove the capacitative compensation from the Main St. and Miguel substations. For this case, the average SDG&E substation node voltage was 93.2% of the nominal operating voltage. This is below the industry accepted 95%, and resembles the low voltages that occurred in PJM in 1999.

Although normal voltages occurred elsewhere in WSCC, the SDG&E node voltages could not be maintained by transmitting reactive power into SDG&E from elsewhere. By constraining reactive-power production by allocating all available capacity in SDG&E to the production of real power, a situation resulted in which the control of a few substation capacitors exerted a nearly monopolistic control of voltage support in the SDG&E area. We conclude that marketplace rules for trade in reactive power generation must be crafted carefully, to assure sufficient reactive generation is distributed as needed throughout the electric-power transmission infrastructure. Otherwise, some type of regulation of this service may be necessary to prevent unique resources from exerting unfair or monopolistic market power.

5. Acknowledgments

This paper was supported by the LANL Electricity-Infrastructure Simulation System (ELISIMS) project. ELISIMS is a comprehensive simulation of the North American electric-power grid, with detail to represent the operation if individual infrastructure components and encompassing the scope of the industry to include the interactions between economic marketplaces and engineering systems. Analyses in this paper used power-flow calculation software obtained from the University of Texas-Arlington's Energy Systems Research Center. Data for these analyses were obtained from Cal-ISO through a cooperative research and development agreement (CRADA) with LANL.

6. References

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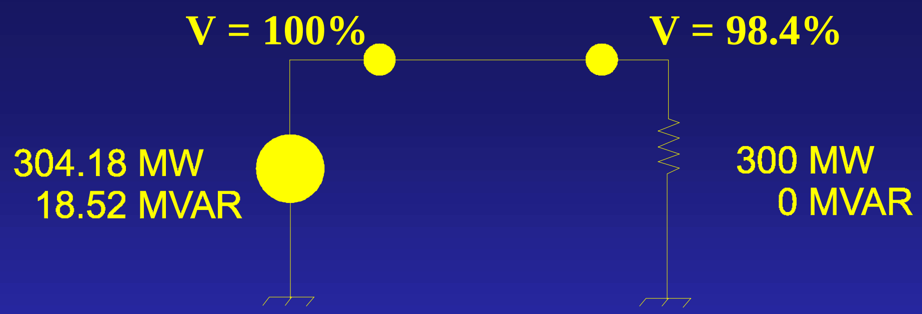

Figure 1. A generating node and a customer node connected by a single transmission line. The 115-kV transmission line impedence is 0.026 p.u. reactive, 0.0045 p.u. resistive, with 0.0574 p.u. charging capacitance.

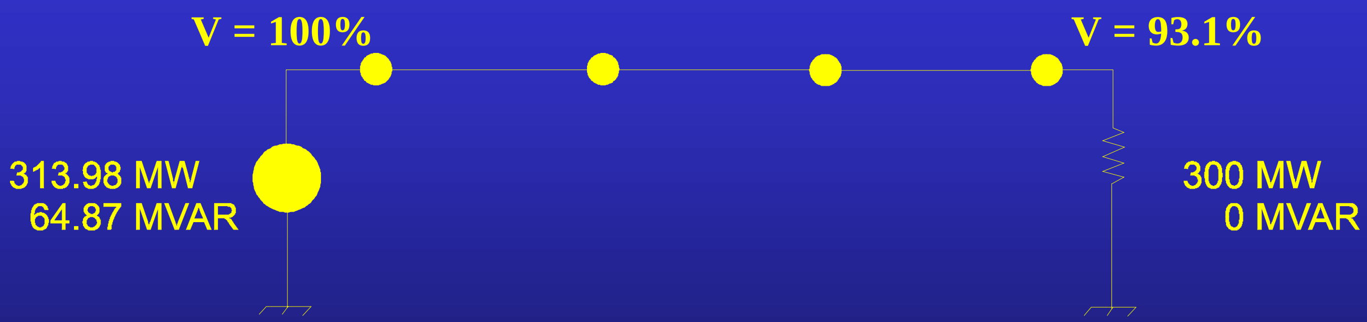

Figure 2. The same generation and customer nodes, here connected by three transmission lines having the same parameters..

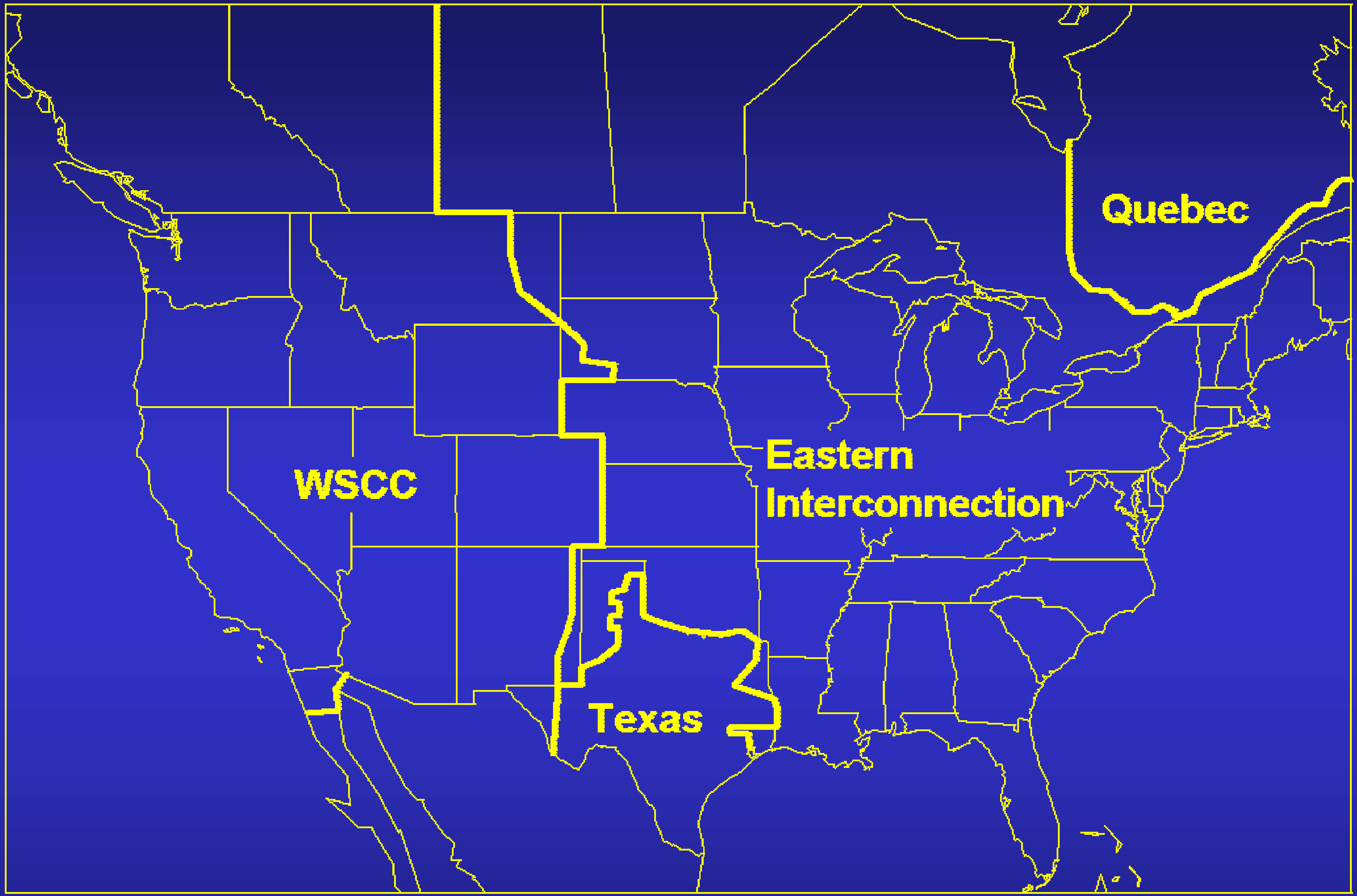

Figure 3. The Four Electric-Power Interconnections Comprising the Continental United States.

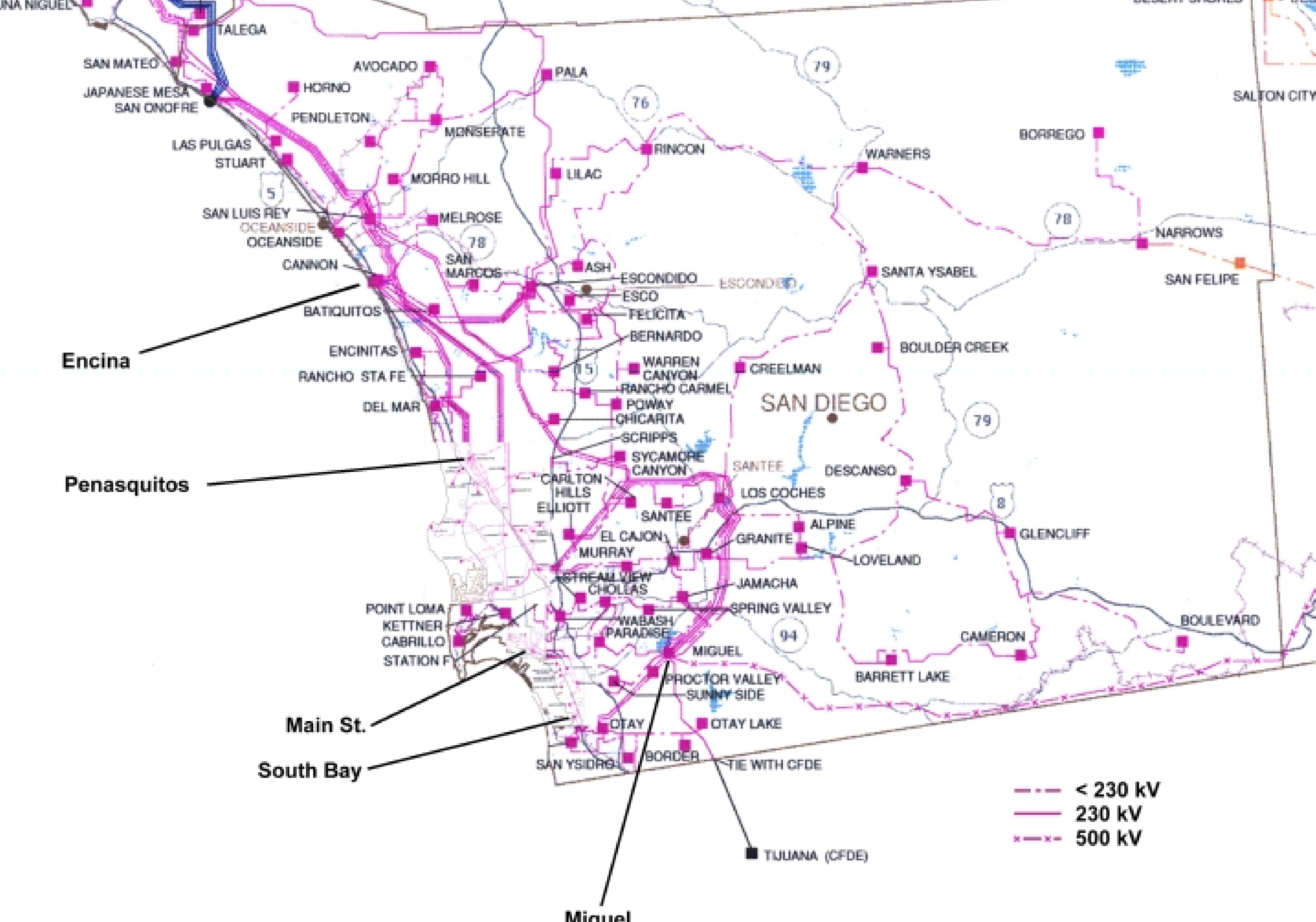

Figure 4. San Diego Electric-Power Infrastructure